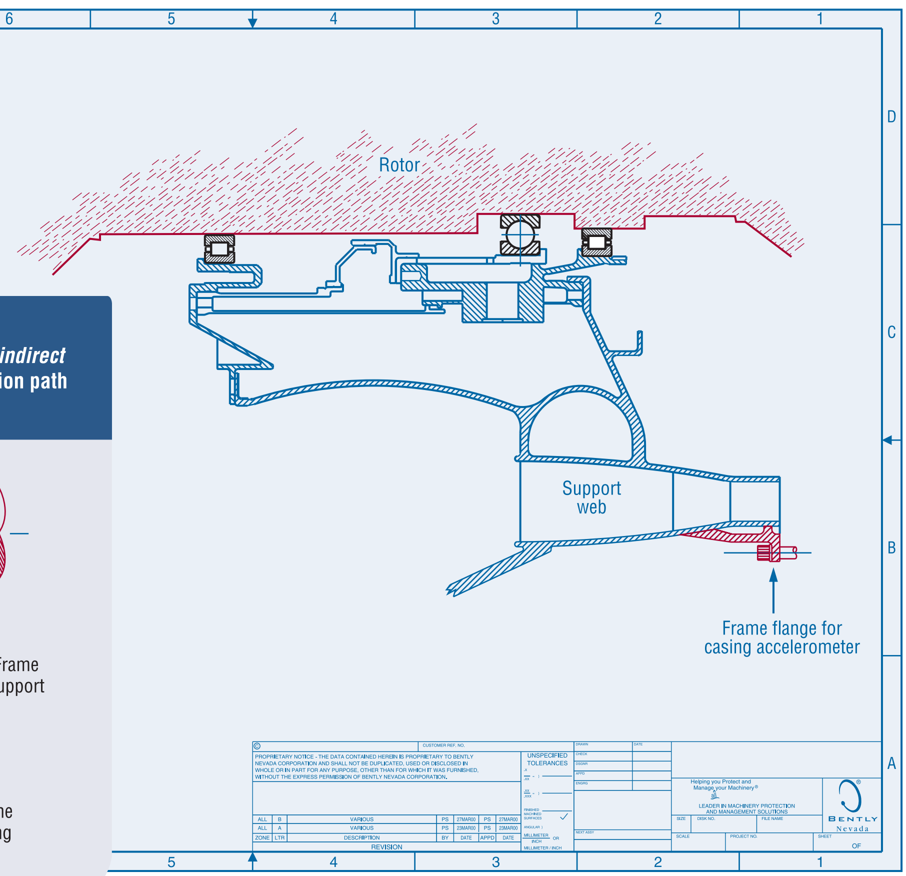
Aeroderivative Internal Transducer Design

Authored by:

Peyton Swan
Principal Engineer, Machinery Diagnostics Team
Bently Nevada Corporation
e-mail: peyton.swan@bently.com

Aeroderivative gas turbines are a popular prime mover due to their high efficiency and packaged designs. While these machines are typically fitted with casing vibration monitoring, and have been for many years, it is rarely adequate, particularly when compared to the shaft vibration monitoring systems generally available on industrial (i.e., non-aeroderivative) gas turbines. Without exception, the standard monitoring scheme for aeroderivatives has been to place one or more casing vibration transducers, usually accelerometers, on the main frame members of the outside casing, usually in the vicinity of the bearings. There are many documented cases of engine failures and significant mechanical malfunctions that are not



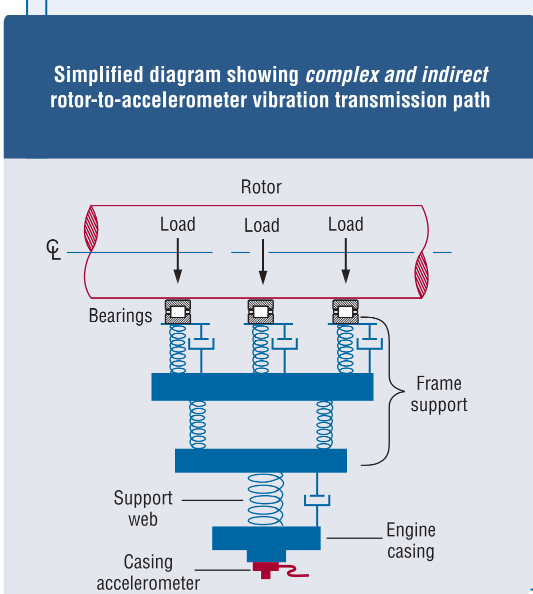


Figure 2.

Figure 1 – Measurement location for casing accelerometer-based system relative to rotor/bearing system. Vibration transmission path is complex and indirect, resulting in data of limited diagnostic and protection value.

Unfiltered half spectrum of typical aeroderivative engine casing accelerometer signal

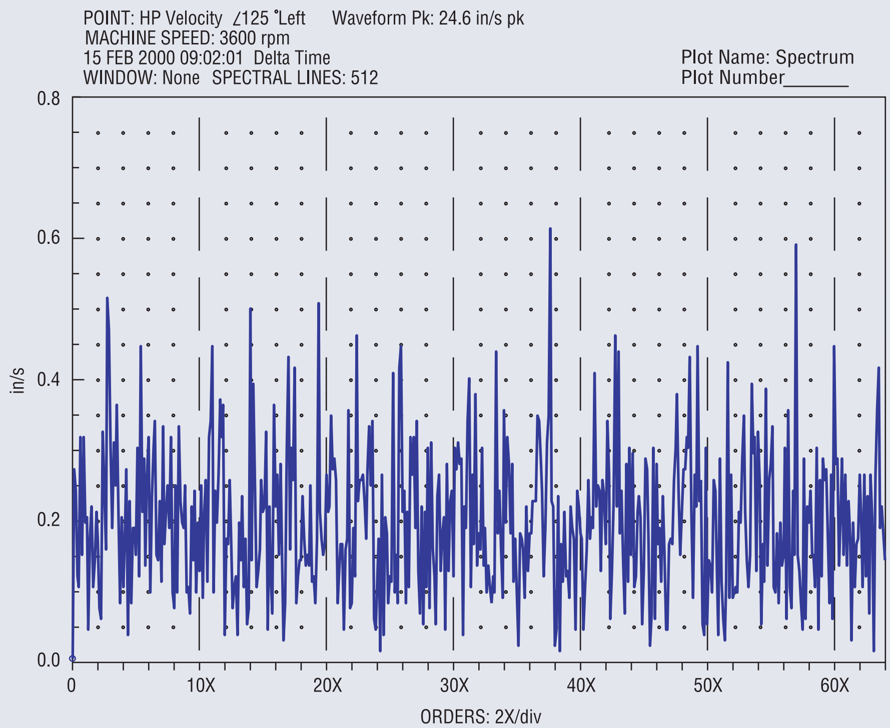


Figure 3.

detected by these conventional approaches to aeroderivative vibration monitoring, and the ability to perform detailed diagnostics on the machine is likewise limited due to a lack of appropriate measurements and instrumentation.

The reasons behind this limited monitoring methodology were twofold. First, to address vibration transducer failures, they had to be placed where replacement could be easily accomplished. Second, the vibration transducers were generally viewed as emergency trip switches for catastrophic events such as a broken blade. One original equipment manufacturer (OEM) has referred to this method as "carcass" monitoring, as opposed to an engine health and diagnostic tool. Figures 1 and 2 show a section of an engine and are typical of just how indirect the load path from rotor to transducer actually is.

Add engine structural frequencies to the problem of rotor load path attenuation and it becomes evident that diagnosing engine problems from casing signals is challenging at best. In an effort to combat this broad mix of signals, modern casing transducer monitoring systems are designed to heavily filter the accelerometer signals, often to only rotor 1X or to a narrow band-pass frequency range, typically 25 Hz to 350 Hz. Figure 3 shows an unfiltered casing accelerometer signal illustrating the broad mix of rotor, combustion, aerodynamic, structural, and blade-pass components present. Extraction of meaningful diagnostic or condition information from such a signal is virtually impossible.

Furthermore, the absence of a Keyphasor® transducer to provide exact phase and speed information compounds the problem of getting good diagnostic data from these engines. Without exception, every aeroderivative engine produced today lacks a true once-per-turn Keyphasor signal from the rotor. Speed signals are often taken from probes looking at gear teeth several gears away from the rotor, producing ratios such as 44.94480287 events/revolution. Phase data is impossible to get without using pulse multiplier/divider circuitry accurate to at least 6 significant digits past the decimal point. Even then, the reference is only good for the duration of a run.

Stiffness Considerations

Another way to illustrate the concepts we have introduced thus far is to consider the dynamic stiffness properties of the structural elements between the rotor/bearing system and the measurement location.

Dynamic motion measured in displacement or acceleration engineering units is defined by the following relationship:

$$\text{Dynamic motion} = \frac{\text{Force}}{\text{Dynamic Stiffness}}$$

In our case, the forces we are interested in originate within the rotating system. They can result from malfunctions such as mass unbalance, misalignment, rotor-to-stator rubs, aerodynamic blade passing, thermal bows, etc. They can also result from roller bearing degradation due to inner race, outer race, or cage defects. The rolling element bearings and each structural member in the force transmission path serve to attenuate the transmissibility of forces between the rotating system and the measurement location. Therefore, the observed dynamic motion at the external casing of the aeroderivative engine will be attenuated. This significantly reduces the effectiveness of casing transducers and their associated monitoring systems.

Bearing-observing REBAM® transducer signal from typical gas turbine engine

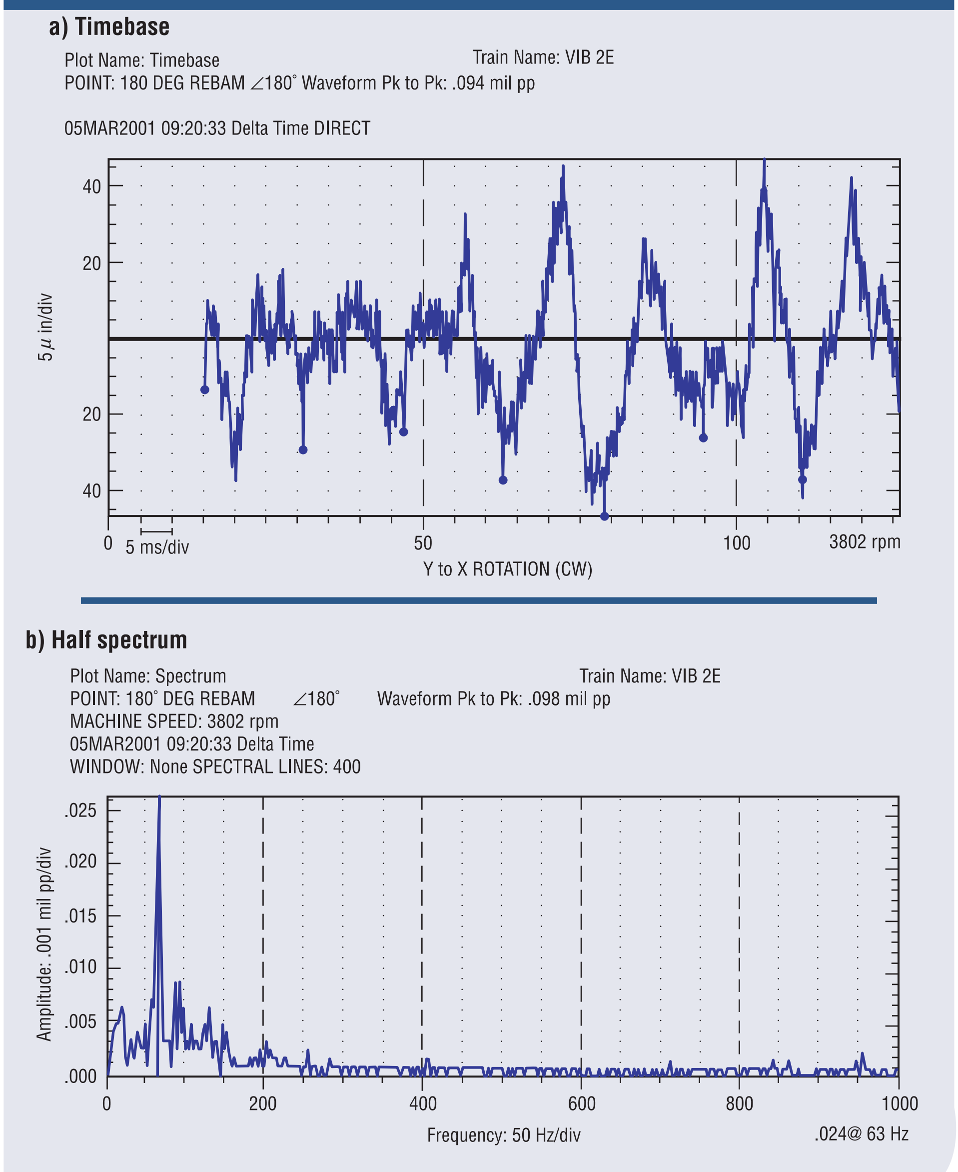


Figure 4.

A Better Way

An engineering principle closely adhered to by Bently Nevada is that the closer the transducers are to the source of the action (the rotor), the better the information regarding the condition of the rotor system. Bently Nevada, in cooperation with numerous end-users willing to explore new territory, has embarked on a program to design and retrofit internal vibration transducers into critical engine areas on several different aero-derivative engine types. Presently, designs for two of the most widely used engine types are complete, with one already installed and operational.

The internal transducer design detailed in this article was developed for a widely used engine. The design places REBAM® transducers directly on the bearing outer races. In addition, a Keyphasor® transducer provides a true once-per-turn phase reference signal from the high-speed shaft. REBAM®

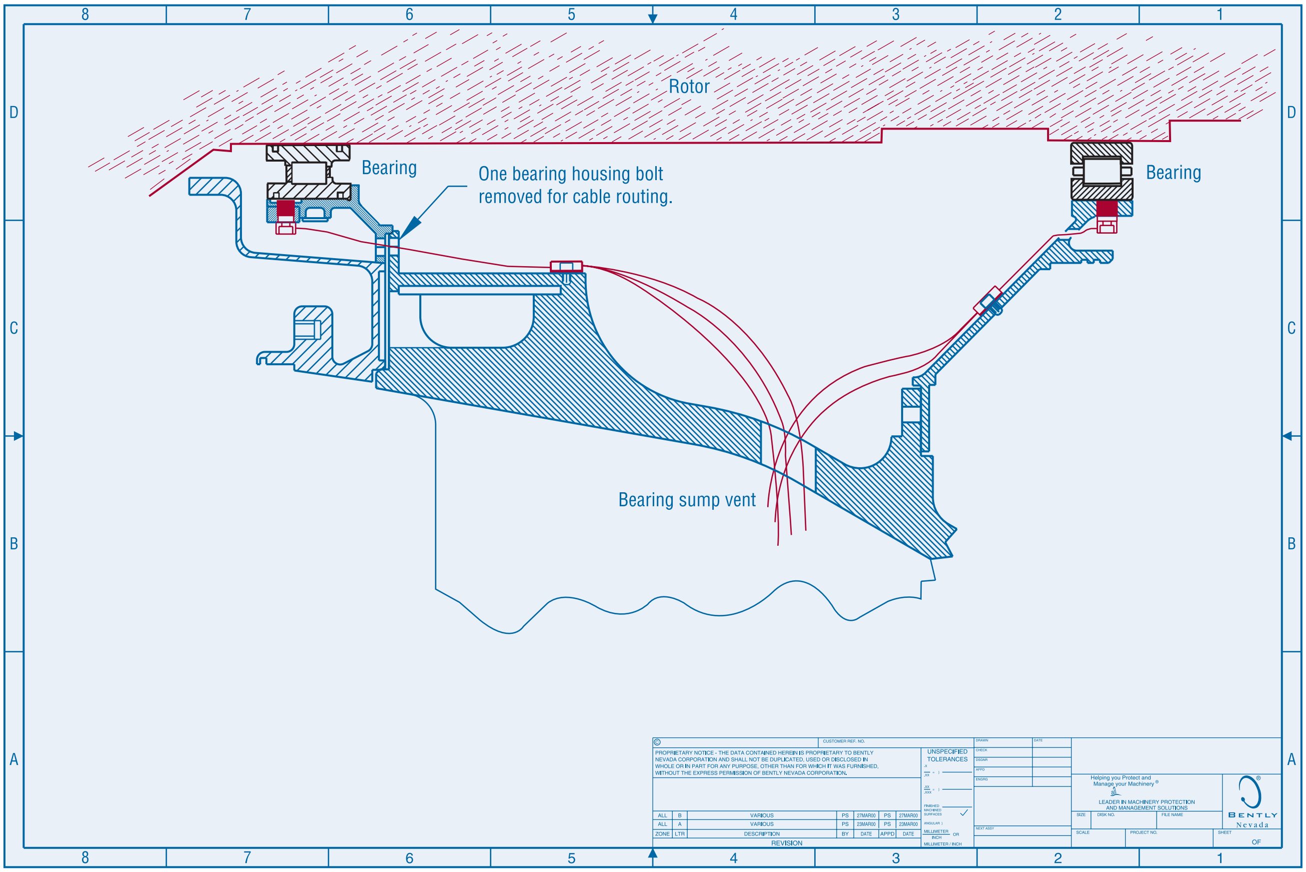


Figure 5 – #2 and #3 bearing compartment. REBAM® probes and cables noted in red, bearings in black.

refers to Rolling Element Bearing Activity Monitor probes (see sidebar on page 56). Unlike casing accelerometers, REBAM® transducers directly observe the machine's bearings and inherently have a high signal-to-noise ratio. They provide both bearing-related data (such as worn rolling elements or races) and rotor-related data (such as imbalance). Figures 4a and 4b show frequency- and time-domain signals from a REBAM® transducer mounted to observe the outer race of a bearing in a typical aeroderivative gas turbine. In contrast with signals from typical casing-mounted accelerometers (Figure 3), diagnostic information can be easily extracted from these signals (see our companion article on page 12 for additional information on interpreting signals from REBAM® transducers). Cabling for the transducers is routed via the bearing sump vent lines and out through seals installed in the line at the top of the engine.

Figure 5 shows a cross-section of the second roller bearing and third roller bearing in one of the sumps within the engine front frame. These bearings support the rear of the low-pressure (LP) and front of the high-pressure (HP) compressor shafts. The REBAM probes are mounted through the bearing housings and view the bearing outer races at the bottom dead center of the races. This location within the gravity load path provides the REBAM probes with the best view of the bearing outer race deflection caused by bearing defects. In addition, the probes provide information on rotor-related vibrations due to mass unbalance changes, internal rubs, radial preloads, etc.

Figure 6 illustrates the cross-section view of a sump housed within the Compressor Rear Frame case of the engine. The fourth roller, fourth ball, and fifth roller bearings are contained within this sump. Similar to the #2 and #3 mountings, transducers on these bearings are mounted at bottom dead center in the gravity load path to provide the best data.

The operating condition for the transducers is an oil spray environment slightly above atmospheric pressure

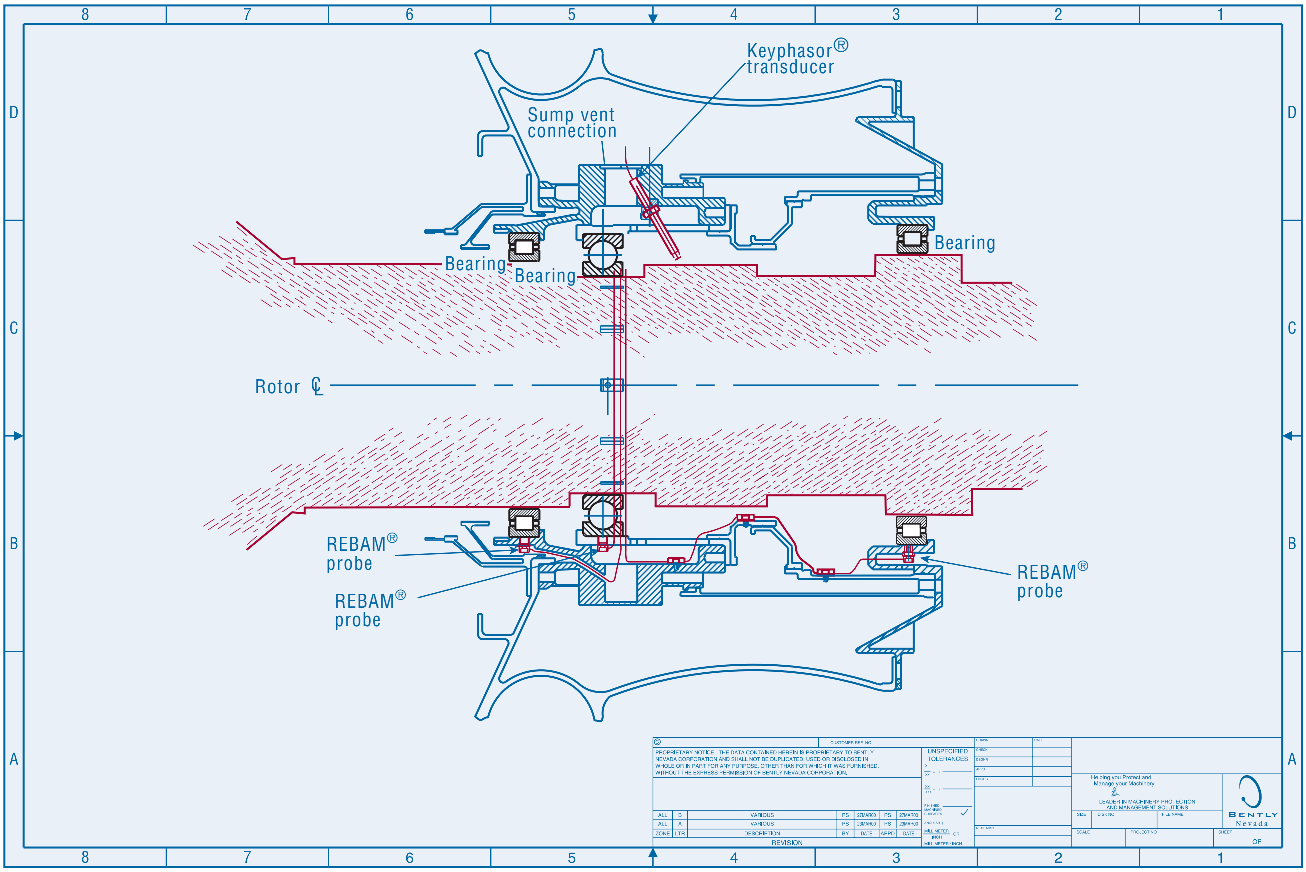


Figure 6 – #4 and #5 bearing compartment. REBAM® probes and cables noted in red, bearings in black.

and well within the probe temperature and pressure limitations. Wiring is ganged with high temperature heat-shrink tubing and secured within the sump housings by stainless steel clips. It is then routed through the respective sump vent piping to an exit seal that has been installed in the common sump vent manifold at the top of the engine.

Nuts & Bolts

Many have expressed concern over the long-term effect of the modification access. To evaluate the effect of drilling holes and modifying the existing engine hardware, a finite element model of each unmodified bearing housing was constructed to investigate stress concentrations around the transducer locations. As shown in Figure 7, detailing the #2 bearing housing, a radial saddle-load of 1000 pounds was applied to the lower half of the bearing housings in the bearing seat areas. The intent was to determine the relative stresses in the bearing housings caused by a known load, the rotor. Once the model was built and the material

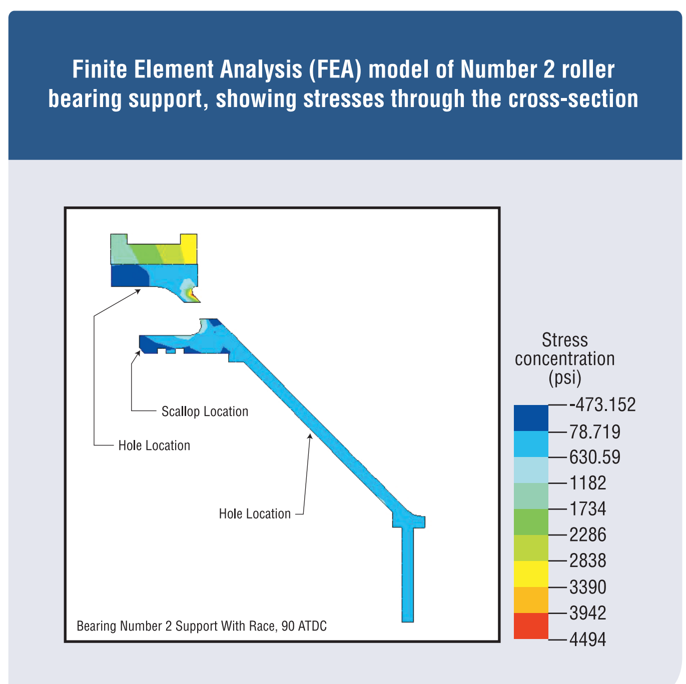


Figure 7.

Finite Element Analysis (FEA) model of Number 4 roller bearing support stresses, showing area of modification

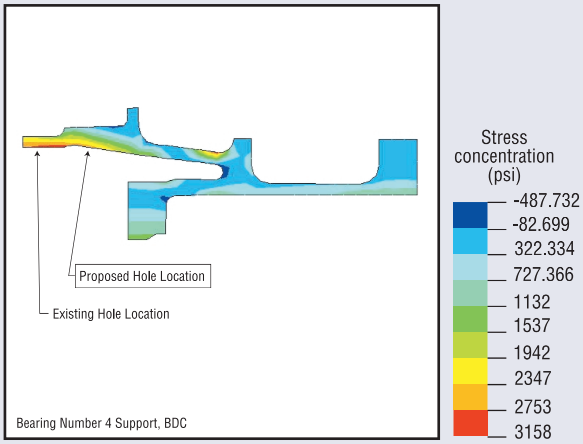


Figure 8.

Finite Element Analysis (FEA) model of Number 5 roller bearing support stresses, showing area of modification

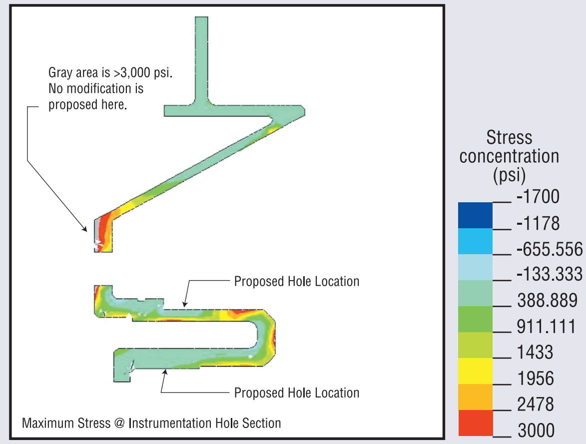


Figure 9.

stresses at the transducer locations were known, Peterson's[1] stress concentration factors for holes ($K_{tg} = 3.4$) was used to determine the stresses around the proposed modifications. In all but the #5 bearing housing, the highest stress concentrations were located approximately 90 degrees around the housing from the proposed transducer locations, which placed the proposed modification stresses well within material service limits. Figure 8, the #4 bearing housing, shows the typical location of the high stress regions. Although the highest stress concentrations in the #5 bearing housing were in the lower portion of the housing, as shown in Figure 9, they were outside of the modifications needed for the transducer installation and well within the material service limits.

Managing Below the Alert Level

Most people will readily agree that conventional approaches to vibration monitoring for aeroderivatives are less than adequate compared to the way other turbomachinery is commonly instrumented today. While the details of mounting vibration probes inside an aeroderivative engine can be challenging, it is not necessarily any more challenging than the obstacles faced by Bently Nevada as we helped industry instrument other types of machines over the last 40 years. An appropriate question, then, is not "Can it be done?" but "Should it be done?" The answer to that question lies in the Return On Investment that can be expected once better instrumentation is installed. The numbers are indeed compelling: a single catastrophic engine failure prevented (or caught in the early stages) can be worth 100 to 200 times the initial transducer hardware investment. These numbers do not even take into account the cost of lost production or additional plant maintenance resulting from a typical engine failure.

Design drawings for this internal transducer system have been submitted to the OEM for review. If you are interested in getting better information from your engines for proactive machinery management, internal vibration transducers are the answer. Bently Nevada's scope of expertise encompasses not only the instrumentation, but also the ability to analyze your machine's design and recommend appropriate modifications to your machine, allowing it to accommodate our transducers. We can even perform the modifications and install the instrumentation for you. If your aeroderivatives can benefit from improved instrumentation, we can help. Contact the author or your local Bently Nevada sales or service professional for more information.

[1] Pilkey, Walter D., *Peterson's Stress Concentration Factors*, second edition, John Wiley & Sons, Inc., 1997, p. 256.